

Research Report  
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**EFFECTS OF CONSTRUCTION VARIATIONS  
UPON DYNAMIC MODULI OF ASPHALTIC CONCRETE**

by

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## INTRODUCTION

The two variables that most influence the behavior of asphaltic concrete pavements are subgrade modulus and thickness of the asphaltic concrete. Other significant variables are: temperature of the asphaltic concrete, asphaltic concrete modulus, frequency of the dynamic loading, asphalt content by weight in mix, and voids in the asphaltic concrete mix.

During a series of Road Rater tests on a experimental pavement in Kentucky, deflection test data varied widely from expected values. Test data reported by Kallas and Riley (1) permitted the development of an equation relating asphaltic concrete modulus to its temperature and to the frequency of loading. However, after deflection data were adjusted for temperature and frequency, the variation was still greater than expected. Construction records for each test station were examined; the void content and asphalt cement content of the mix were found to vary considerably.

## LABORATORY DATA

Kallas and Riley reported results of tests illustrating the interdependency of mix temperature, frequency of cyclic loading, and modulus of asphaltic concrete. The data in Figure 1 is very closely described by

$$E^* = 10^{[(a+b(^{\circ}F)+c(^{\circ}F)^2) + (d+e(^{\circ}F)+f(^{\circ}F)^2)(\log_{10} \text{ Hz})]}$$

1

in which

$E^*$  = complex modulus of elasticity of the asphaltic concrete,

$^{\circ}F$  = temperature, degrees Fahrenheit,

Hz = frequency of loading, cycles per second,

$a = 6.763855405$ ,

$b = -0.0072846915$ ,

$c = -0.0001108391$ ,

$d = -0.1741191221$ ,

$e = 0.0074997275$ , and

$f = -0.0000180328$

Shook and Kallas (2) reported changes in the modulus of elasticity of asphaltic concrete as a function of temperature, frequency of loading, and asphalt cement content and void content of the asphaltic concrete mix. Selected results from their Tables 4 and 5 have been selected and presented here in Table 1. Each data value was the average of three tests. Detailed inspection prompted the request for the individual test data, which Mr. Kallas graciously supplied.

## DATA ANALYSES

Typical mix designs for Kentucky aggregates will contain five percent asphalt and four percent voids. The mean annual temperature for Kentucky is  $70^{\circ}F(21.1^{\circ}C)$ . Equation 1 permits adjusting the modulus at any temperature to an equivalent modulus at  $70^{\circ}F(21.1^{\circ}C)$ . Equivalent moduli for Kentucky conditions is 480 ksi (3.31 GPa) at 0.5Hz and 1,200 ksi (8.27 GPa) at 25 Hz.

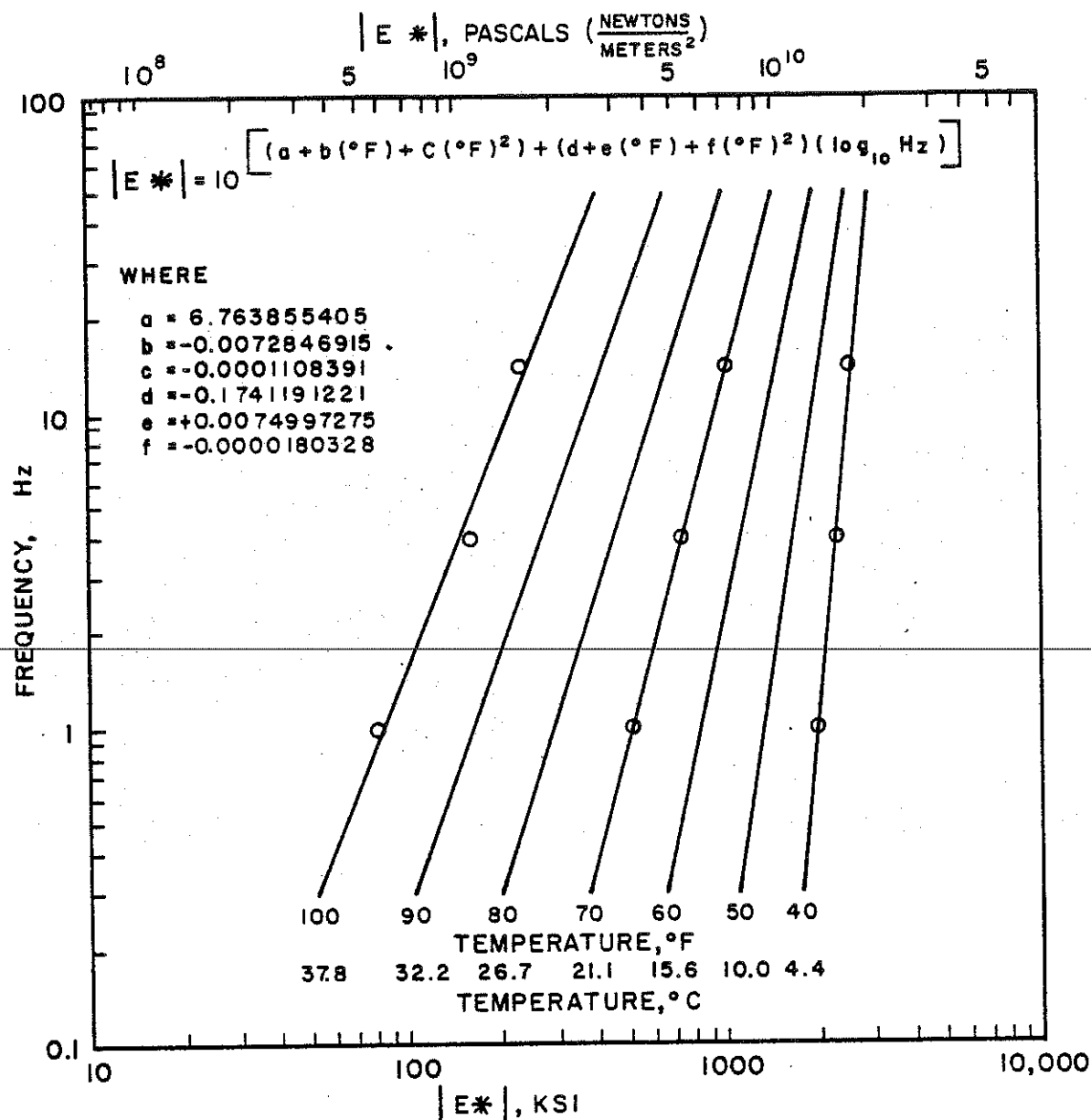


Figure 1. Relationship of temperature, frequency of loading, and modulus of asphaltic concrete.

Table 1. Test Data (Series 5-1 from Tables 4 and 5 Reported by Shook and Kallas (2)).

Code (1). No.	Air Voids Content %	Asphalt Content %	Dynamic Modulus ( $E^*$ ), $10^5$ psi								
			1 cps (2)			4 cps			16 cps		
			40°F	70°F	100°F	40°F	70°F	100°F	40°F	70°F	100°F
5-1-4	6.6	4.0	15.3	3.85	1.40	19.3	5.70	2.05	22.8	8.75	3.05
5-1-4	10.3	4.0	9.20	2.55	0.55	11.8	3.90	0.80	13.7	5.50	1.20
5-1-4	12.3	4.0	6.50	1.50	0.55	8.30	2.45	0.75	11.5	3.65	1.05
5-1-5	3.8	5.0	15.7	4.35	1.25	19.2	6.30	1.95	23.6	9.50	2.80
5-1-5	7.2	5.0	9.85	2.85	0.55	12.7	4.00	0.90	16.1	5.65	1.40
5-1-5	9.3	5.0	8.05	1.75	0.50	10.9	2.90	0.75	13.1	4.00	0.95
5-1-6	0.6	6.0	13.5	3.70	1.00	17.5	5.50	1.50	21.0	8.45	2.00
5-1-6	4.5	6.0	10.3	2.90	0.65	13.3	4.25	0.95	17.6	5.75	1.45
5-1-6	6.1	6.0	7.95	2.00	0.50	10.3	3.25	0.75	13.1	4.90	1.15

Data from Shook and Kallas Series 5-1 can be expressed by the equation

$$E^* = K_1 + K_2 V + K_3 V^2 \quad 2$$

in which

$V$  = percent voids in the mix and

$K_1, K_2, K_3$  = constants defined by polynomial equations involving log frequency, percent asphalt content, and temperature in degrees Fahrenheit.

To define each of the three constants involved nine equations and 27 constants. Thus, to fully define  $K_1, K_2$ , and  $K_3$  required 27 equations and 81 constants, each of which required a minimum of six digits to maintain accuracy.

The Kentucky procedure for analyzing deflection tests asphaltic concrete pavements requires adjusting the measured deflections to comparable values at 70°F(21.1°C). Thus, one variable in defining the constants of Equation 2 was fixed at 70°F(21.1°C). The complex modulus  $E^*$  was calculated by Equation 2 for frequencies of 1, 4, 16, and 25 Hz and reference condition of five percent asphalt content and four percent voids. The modulus was calculated for each combination of asphalt content and voids content shown in Table 1. The modulus calculated by Equation 2 was approximately half of the value for Kentucky conditions as determined by dynamic deflection test procedures (3). However, Equation 2 is valid only for the specific asphalt and aggregate used in the mix tested by Shook and Kallas (2).

The ratio of complex modulus for any mix to that for a mix at reference conditions would enable the application of research by Shook and Kallas to other test data.

$$\text{Ratio} = \text{Modulus for } X\% \text{AC, } Y\% \text{ Voids} / \text{Modulus for } 5\% \text{AC, } 4\% \text{ Voids} \quad 3$$

The reference conditions chosen for Kentucky analyses are defined as 70°F(21.1°C), five percent asphalt cement content, and four percent voids. The resulting ratios are shown in Figure 2. Close inspection of Figure 2 reveals that the ratios for frequencies of 4, 16, and 25 Hz were almost identical up to nine percent or more voids. Ratios for 1 Hz varied considerably from the other frequencies. Most dynamic testing utilizing constant frequency loadings will be in the range of 6 to 40 Hz, depending upon the test machine and the choice of operating frequencies. Thus, for normal test conditions, the ratios for 1 Hz were eliminated. The relationship between ratio, percent voids, and percent asphalt cement content is expressed as:

$$\log \text{Ratio} = R + S (\%V) + T (\%V)^2 \quad 4$$

in which

$$R = -7.215174975 + 3.057898967 (\% \text{AC}) - 0.311822159 (\% \text{AC})^2,$$

$$S = 2.031971246 - 0.8295219679 (\% \text{AC}) + 0.0818557973 (\% \text{AC})^2, \text{ and}$$

$$T = -0.1248532048 + 0.501973099 (\% \text{AC}) - 0.0050377741 (\% \text{AC})^2.$$

Equation 4 was used to calculate the ratio that was compared to the ratio from Equation 3, and the correlation is shown in Figure 3. While Equation 4 contains coefficients of 10 digits, reasonable ratios may be obtained with a minimum of six digits which are needed because of the squared terms.

When a mix is designed to have an asphaltic cement content and/or voids content different than the reference values of 5 and 4 percent, respectively, Equation 4 can be used to determine the proper adjustment factors for the "design" mix. The as-constructed values for the new mix are substituted into Equation 4 to determine the ratio based upon the "reference" mix. Percentages for the design mix are substituted in-

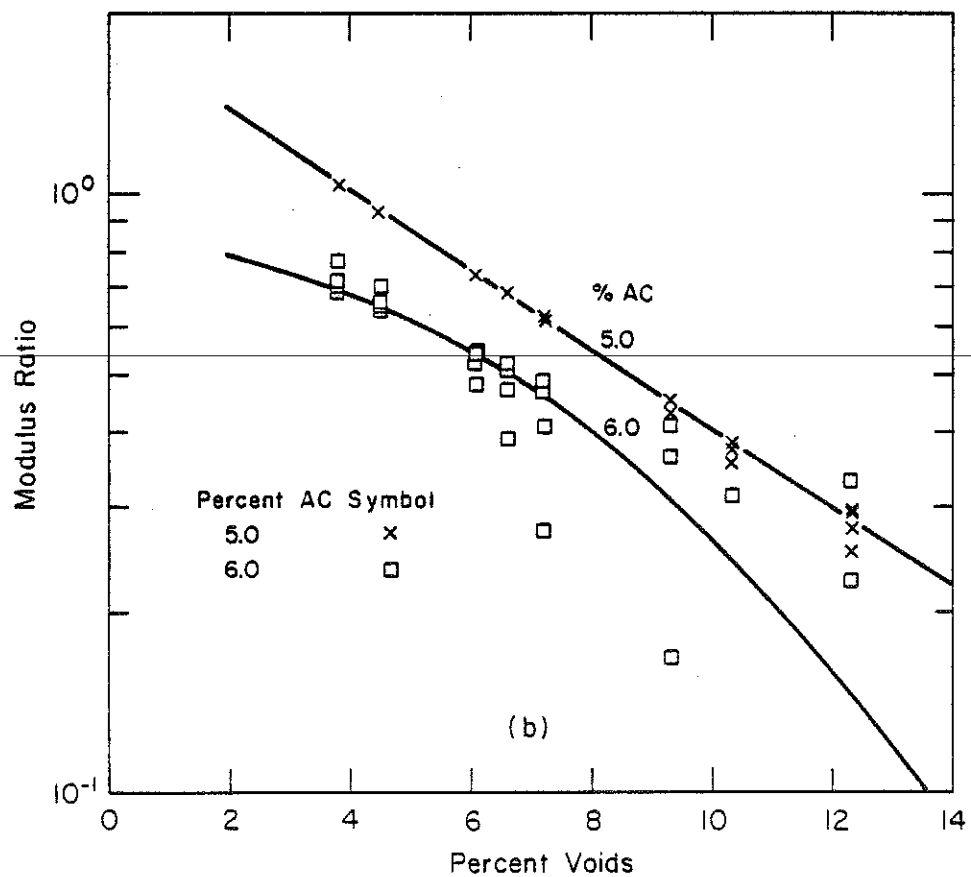
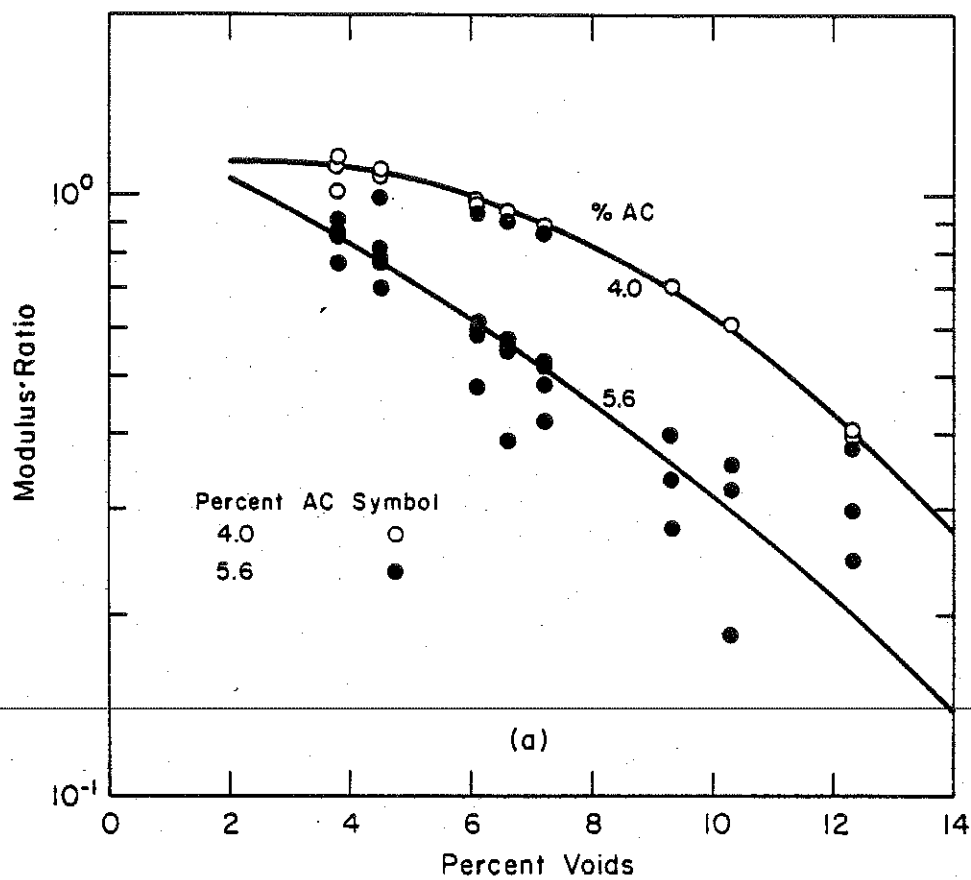


Figure 2. Complex modulus as a function of asphalt cement and voids contents in asphaltic concrete.

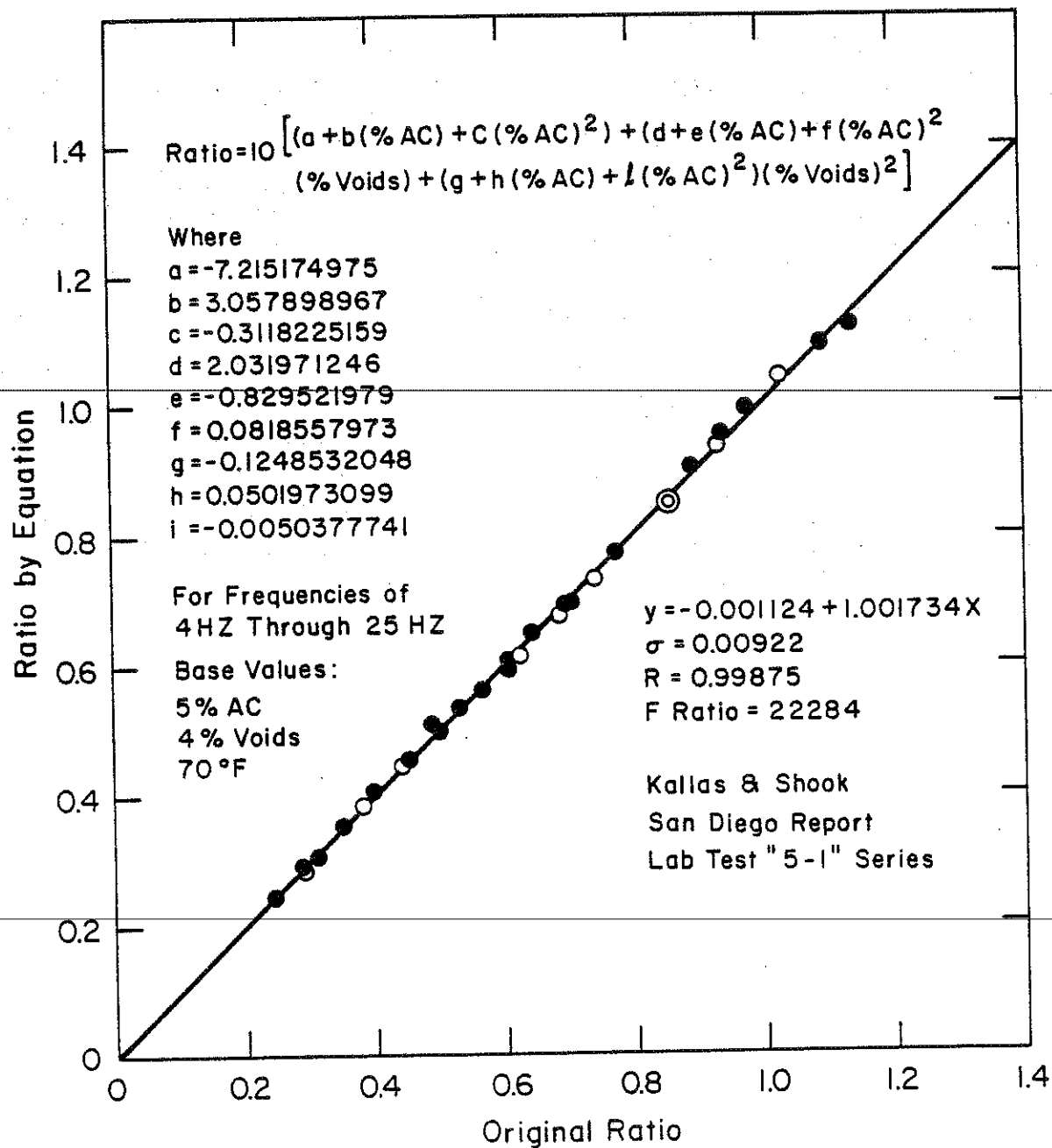


Figure 3. Correlation of ratios of complex moduli from test data and from equation 4.

to Equation 4 to determine the "design adjustment ratio." The proper adjustment factor for the as-constructed data for that particular mix design is the ratio of the as-constructed ratio to the design ratio, as shown by the following example:

Design Mix: 5.5%AC, 5% Voids, Ratio from Equation 4 = 0.78185

As-constructed 5.5%AC, 6% Voids, Ratio from Equation 4 = 0.63575

Ratio of As-constructed to Design Mix = 0.63575/0.74185 = 0.857

Tables 2a and 2b contain data for the shoulder and median lanes, respectively for the same test stations.

## SIGNIFICANCE OF VOID CONTENT

Detailed records for each section at the AASHO Road Test were reviewed to determine the overlaid sections and the measurement of rut depth after the overlay. Most overlays were 3 inches (76.2 mm) of asphaltic concrete. Within three months of completion of the overlay, average measured rut depth was 0.15 inches (3.8 mm). Assume that 98 percent density was the design level for an assumed 3 percent void content. If construction methods produced an 8 percent void content, then the reduction of void content to 3 percent will result in 0.15 (3.8 mm) inches of rutting (3 inches (76.2 mm) x 0.05 percent voids).

## EXPERIMENTAL PAVEMENTS

Six sections of full-depth asphaltic concrete were constructed in 1971 on US 60, Boyd County, Kentucky (4). Nominal thicknesses ranged from 10 to 18 inches (254 to 457 mm). Construction of each lift of asphaltic concrete was monitored by nuclear density tests and dynamic testing using a Road Rater. Construction records were examined for the section from Station 245+00 to Station 285+00. A 16.9-inch (429 mm) core was retrieved from the pavement at Station 279+50. The asphalt cement and void contents for each layer at each test station are given in Table 2, and variability is rather large.

Road Rater tests made in 1979 were used to determine the "effective thickness" at each test station. The temperature distribution was estimated by the Southgate method (5), and temperatures were inserted in Equation 1 to obtain the estimated moduli distribution at the time of test. The deflections had been adjusted to reference conditions of 70°F (21.1°C) and a modulus of 1,200,000 psi (8.27x10<sup>9</sup> GPa) at 25 Hz. The "behavioral" thickness at Station 279+50 was determined to be 16.6 inches (429 mm) (Table 2). Asphalt cement and void content were inserted into Equation 4 to determine the adjustment ratios for these parameters. Multiplying the moduli from Equation 1 by the ratios from Equation 3 gave the adjusted modulus for each layer as shown in Table 2. The weighted average was determined by

$$|E^*|_{\text{average}} = \frac{\sum_{n=1}^{n=6} L(n) \times E(n)/16.9 \text{ inches}}{5}$$

in which

n = layer number, Layer 6 being the surface layer,

L(n) = thickness of layer "n", and

E(n) = modulus of layer "n".

The factor to adjust deflections measured by the sensors of a Road Rater to account for variations in mod-

ulus is given by

$$\log AF_j = \frac{[\log AC - (H_1 E_{AC}^3 + H_2 E_{AC}^2 + H_3 E_{AC} + H_4)]}{[M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4]} \quad 6$$

in which

$H_1, H_2, H_3, H_4, M_1, M_2, M_3,$  and  $M_4$  = constants for each sensor,  $j$  (Table 3),

$E_{AC}$  = mean or "weighted" asphaltic concrete modulus, psi

$AC$  = thickness of asphaltic concrete pavement, inches, and

$j$  = Road Rater sensor number.

The measured deflections were adjusted by the factor from Equation 6 and analyzed by the procedure reported elsewhere (3). The "effective" thickness by deflection tests was determined for each station and is given in Table 2. Using the weighted modulus to account for variations in asphalt cement and voids contents, the average behavioral thickness determined by 24 dynamic deflection tests was reduced by 0.5 inch (13 mm) due to construction variabilities in the layers. The 0.5-inch (13 mm) reduction in effective thickness will result in a 20 percent decrease in the fatigue life. Analyses using the Chevron N-layer computer program and the calculated moduli of Table 2 should produce more accurate analyses than using the weighted modulus method, but that analysis has yet to be accomplished.

## CONCLUSIONS

Improper construction methods will cause variability in asphalt cement and/or voids contents. The complex modulus can be substantially reduced, leading to rutting, higher deflections than expected, behavior as that of a thinner pavement, and reduction of the fatigue life. The method presented herein can be used to estimate the loss of fatigue life and/or the reduction of effective thickness. The method reported herein was based upon tests of mixes containing one source of aggregate and one source of asphalt cement. Verification and/or modification to the method reported herein using other asphalt cements and aggregates is needed.

## ACKNOWLEDGEMENT

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Table 2. Construction Data for Research Pavement, US 60, Boyd County, Kentucky.

SHOULDER LANE													
STATION NUMBER	NUMBER	THICKNESS INCHES	TEMPERATURE DISTRIBUTION %	E* , KSI	BEHAVIORAL THICKNESS INCHES		ASPHALT			ADJUSTED  E* , KSI	WEIGHTED  E* , KSI	ADJUSTED BEHAVIORAL THICKNESS	
					OUTER	INNER	VOIDS	CONTENT	RATIO			OUTER	INNER
247+50	SURFACE	1.1	76	950	15.8	13.7	2.4	5.7	0.9584	911	664	16.5	14.7
	5	3.2	70.5	1174			3.4	5.4	0.9794	1150			
	4	3.9	71	1153			6.1	5.6	0.6068	700			
	3	3.3	71	1153			8.7	5.8	0.3692	426			
	2	3.5	72	1111			7.5	5.0	0.5889	654			
	1	1.9	72	1111			6.6	6.1	0.4856	539			
262+00	5	1.1	76	950	15.0	13.0	3.6	6.4	0.5338	507	859	16.0	14.7
	5	3.2	70.5	1174			3.3	6.4	0.5311	624			
	4	3.9	71	1153			2.6	5.0	1.2590	145			
	3	3.3	71	1153			7.6	4.6	0.6732	776			
	2	3.5	72	1111			7.6	4.5	0.7003	778			
	1	1.9	72	1111			6.6	6.1	0.4856	539			
264+00	5	1.1	76	950	15.5	15.5	3.5	6.2	0.6199	589	622	16.9	16.5
	5	3.2	70.5	1174			0.7	5.7	1.1397	134			
	4	3.9	71	1153			11.2	5.4	0.2437	281			
	3	3.3	71	1153			7.6	4.6	0.6732	776			
	2	3.5	72	1111			10.2	5.2	0.3580	398			
	1	1.9	72	1111			9.2	6.7	0.2516	280			
271+00	5	1.1	76	950	16.9	15.0	2.4	5.5	1.0807	103	714	15.7	16.9
	5	3.2	70.5	1174			4.7	5.5	0.7762	912			
	4	3.9	71	1153			2.6	5.3	1.1508	133			
	3	3.3	71	1153			1.1	7.2	0.0871	100			
	2	3.5	72	1111			9.0	4.3	0.6318	702			
	1	1.9	72	1111			14.4	6.7	0.0236	262			
273+50	5	1.1	76	950	15.0	13.8	2.4	5.2	1.2313	117	527	14.5	15.0
	5	3.2	70.5	1174			0.6	6.0	0.8050	945			
	4	3.9	71	1153			2.4	7.1	0.1962	226			
	3	3.3	71	1153			0.0	6.9	0.1093	126			
	2	3.5	72	1111			7.5	5.0	0.5889	654			
	1	1.9	72	1111			8.0	5.4	0.4746	527			
279+50	5	1.1	76	950	16.4	16.9	2.6	5.6	0.9956	946	533	16.6	16.0
	5	3.2	70.5	1174			2.5	6.3	0.5714	671			
	4	3.9	71	1153			5.1	7.0	0.3865	446			
	3	3.3	71	1153			5.2	6.0	0.6014	693			
	2	3.5	72	1111			14.4	4.6	0.2481	276			
	1	1.9	72	1111			7.8	6.2	0.3899	433			
MEDIAN LANE													
STATION NUMBER	NUMBER	THICKNESS INCHES	TEMPERATURE DISTRIBUTION %	E* , KSI	BEHAVIORAL THICKNESS INCHES		ASPHALT			ADJUSTED  E* , KSI	WEIGHTED  E* , KSI	ADJUSTED BEHAVIORAL THICKNESS	
					OUTER	INNER	VOIDS	CONTENT	RATIO			OUTER	INNER
247+50	SURFACE	1.1	85	645	13.8	16.9	2.4	5.7	0.9584	618	673	14.5	16.3
	5	3.2	79.1	836			3.4	5.4	0.9794	819			
	4	3.9	70.5	1172			6.1	5.6	0.6068	711			
	3	3.3	68.5	1262			8.7	5.8	0.3692	466			
	2	3.5	68.5	1262			7.5	5.0	0.5889	744			
	1	1.9	68.5	1262			6.6	6.1	0.4856	613			
262+00	5	1.1	85	645	14.6	15.7	3.6	6.4	0.5338	344	665	15.0	16.1
	5	3.2	79.1	836			3.3	6.4	0.5311	444			
	4	3.9	70.5	1172			2.6	5.0	1.2590	148			
	3	3.3	68.5	1262			7.6	4.6	0.6732	850			
	2	3.5	68.5	1262			7.6	4.5	0.7003	884			
	1	1.9	68.5	1262			6.6	6.1	0.4856	613			
264+00	5	1.1	85	645	12.6	16.2	3.5	6.2	0.6199	400	568	13.0	16.9
	5	3.2	79.1	836			0.7	5.7	1.1397	952			
	4	3.9	70.5	1172			11.9	5.4	0.2437	286			
	3	3.3	68.5	1262			7.6	4.6	0.6732	850			
	2	3.5	68.5	1262			10.2	5.2	0.3580	452			
	1	1.9	68.5	1262			9.2	6.7	0.2516	318			
271+00	5	1.1	85	645	15.0	14.2	2.4	5.5	1.0807	697	670	16.2	15.0
	5	3.2	79.1	836			4.7	5.5	0.7762	649			
	4	3.9	70.5	1172			2.6	5.3	1.1508	135			
	3	3.3	68.5	1262			1.1	7.2	0.0871	110			
	2	3.5	68.5	1262			9.0	4.3	0.6318	798			
	1	1.9	68.5	1262			14.4	6.7	0.0236	298			
273+50	5	1.1	85	645	10.4	13.2	2.4	5.2	1.2313	794	481	10.6	13.5
	5	3.2	79.1	836			0.6	6.0	0.8050	673			
	4	3.9	70.5	1172			2.4	7.1	0.1962	230			
	3	3.3	68.5	1262			0.0	6.9	0.1093	138			
	2	3.5	68.5	1262			7.5	5.0	0.5889	744			
	1	1.9	68.5	1262			8.0	5.4	0.4746	600			
279+50	5	1.1	85	645	14.9	15.5	2.6	5.6	0.9956	642	505	14.8	16.2
	5	3.2	79.1	836			2.5	6.3	0.5714	478			
	4	3.9	70.5	1172			5.1	7.0	0.3865	453			
	3	3.3	68.5	1262			5.2	6.0	0.6014	759			
	2	3.5	68.5	1262			14.4	4.6	0.2481	313			
	1	1.9	68.5	1262			7.8	6.2	0.3899	492			

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Table 3. Constants for Deflection Adjustment Factors for the Kentucky Road Rater.

$$\log AF = (\log AC - (H_1 E_{AC}^3 + H_2 E_{AC}^2 + H_3 E_{AC} + H_4)) \\ (M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4)$$

in which AF= deflection adjustment factor  
AC= asphaltic concrete thickness  
E<sub>AC</sub>= mean modulus of elasticity for asphaltic concrete

J= Road Rater sensor number (1, 2, 3)

### Three Layered Pavements

#### DGA Less Than 8 Inches

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	1.0225763E-19	-4.4990262E-13	7.0628626E-07	-0.37155742
2	4.3336498E-20	-2.2091077E-13	4.5988841E-07	-0.30474423
3	3.3403716E-20	-1.6395133E-13	3.4805071E-07	-0.23820381

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-2.0312535E-19	7.1127654E-13	-8.4587020E-07	0.25466949
2	7.2614981E-20	-1.0302809E-13	-1.3874220E-07	0.46069097
3	1.6419243E-19	-3.3570986E-13	-4.2060526E-08	0.66081522

#### DGA Greater Than or Equal to 8 Inches

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	8.6110078E-20	-3.8725065E-13	6.2848481E-07	-0.34173343
2	3.5850121E-20	-1.8167083E-13	3.8532939E-07	-0.25976352
3	2.1116466E-20	-1.0783377E-13	2.5034102E-07	-0.18049747

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-2.3472762E-20	1.1931522E-13	-2.9552194E-07	0.15345469
2	8.6274124E-20	-1.3810588E-13	-8.8295169E-08	0.42052283
3	1.1280263E-19	1.7456748E-13	-1.3783142E-07	0.60022647

### Two Layered Pavements

J	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>
1	1.0486807E-19	-4.5399608E-13	6.6726565E-07	-0.32106577
2	1.0429773E-19	-4.7586726E-13	7.9423008E-07	-0.44438965
3	9.6133265E-20	-3.9709184E-13	6.8153597E-07	-0.41509883

J	H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	H <sub>4</sub>
1	-1.1966613E-18	3.6419900E-12	-3.3712189E-06	0.40220812
2	8.4194518E-20	-1.0803309E-13	-2.9750845E-07	0.63921054
3	2.8337843E-19	-6.0413664E-13	6.2056443E-08	0.84294820